SOLAR CYCLE VARIATION OF INTERPLANETARY DISTURBANCES OBSERVED AS DOPPLER SCINTILLATION TRANSIENTS

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ABSTRACT

interplanetary disturbances characterized by plasma that is more turbulent and/or moves faster than the background solar wind are readily detected as transients in Doppler scintillation measurements of the near-Sun solar wind. Systematic analysis of over 23,000 hrs of Pioneer Venus Orbiter Doppler measurements obtained inside 0.5 AU during 1979-1987 have made it possible for the first time to investigate the frequency of occurrence of Doppler scintillation transients under solar minimum conditions, and to determine its dependence on solar cycle. Based on a total of 142 transients, Doppler scintillation transient rates vary from a high of 0.22 in 1979 (one every 4.6 clays) to a low of’ 0.077 transients/day in 1986 (one every 13 days), a decrease by almost a factor of three from solar maximum to solar minimum. This solar cycle variation, the strongest yet of any solar wind Doppler scintillation property, is highly correlated with both Sunspot number and the coronal mass ejection rates deduced from Solwind and SMh4 coronagraph observations. These results indicate that coronal mass ejections and Doppler scintillation transients are closely related not just during solar maximum, as occasional individual comparisons have shown in the past, but throughout the entire solar cycle. The magnitudes of the transients, as described by the ratio of peak to pre-transient scintillation levels (EF for enhancement factor), and their distribution with heliocentric distance also vary with solar cycle. While EF tends to diminish with increasing heliocentric distance during high solar activity, it is more evenly distributed during low solar activity. EF is also lower during solar minimum, as 13% of the transients during solar maximum have values exceeding 23, the highest EF observed during solar minimum. These results are consistent with the fact that occasional major fast-moving interplanetary shocks that are observed during solar maximum are very rare during solar minimum.

INTRODUCTION

Interplanetary disturbances and their relationship to solar events, including coronal mass ejections observed in white-light coronagraphs, is a continuing topic of interest in solar wind research (Hildner, 1977; Hundhausen et al., 1984; Wagner, 1984; Sheeley et al., 1985; Schwenn, 1986; Neugebauer, 1988; Kahler, 1988, 1992; Webb, 1991). interplanetary disturbances, distinguished by plasma that is more turbulent and/or moves faster than the background solar wind, readily appear as transients in Doppler scintillation. Although they are observed throughout the inner heliosphere, Doppler scintillation transients are especially useful for investigating disturbances near the Sun, where they bridge the gap between solar observations and direct solar wind measurements beyond 0.3 AU (Woo et al., 1985). Solar wind disturbances are also detected as transients in intensity scintillation (IPS for interplanetary scintillation) (Rickett, 1975; Tappin et al., 1983; Watanabe and Schwenn, 1989), but Doppler scintillation offers some significant features not available with IPS (Woo et al., 1985).

Previous studies that have investigated Doppler scintillation transients have concentrated on times of high solar activity. These have yielded information on the evolution of interplanetary shock propagation near the Sun (Woo et al., 1985), statistics of Doppler scintillation transients based on data collected in 1979-1982 (Woo, 1988), and shown through comparisons with radially aligned *in situ* plasma measurements that many of the transients in 1981-1982 represent interplanetary shocks and their trailing turbulent plasma (Woo and Schwenn, 1991),

The purpose of this paper is to extend the period of Doppler transient study to include solar minimum conditions, and to determine the variation of transients with solar cycle, We do this by taking advantage of the unique and extensive S-band (13 cm wavelength) Doppler tracking data collected by the NASA Deep Space Network during Pioneer Venus Orbiter's remarkably long and successful exploration of Venus.

PVO SCINTILLATION OBSERVATIONS

Although our interest lies in transients during low solar activity, it is necessary to use a data set that covers high solar activity under similar conditions so that the solar cycle variation can be reliably established. The Pioneer Venus Orbiter (PVO) Mission is ideal for this purpose because it spanned a full solar cycle during which superior conjunctions took place about once every 18 months. Most important, however, is the fact that, because PVO returned data on Venus nearly continuously, extensive Doppler tracking and therefore scintillation data were obtained,

While Doppler scintillation is an integrated line-of-sight measurement, due to the approximate $1/R^2$ fall-off in electron density fluctuation with heliocentric distance, it essentially observes the solar wind region in the vicinity of the closest approach point of the radio path. For this investigation, we have chosen a data set that comprises the first six superior conjunctions of PVO that took place in 1979-1987, and includes intervals of ±120 days surrounding each conjunction during which the PVO radio path probed the region of the solar wind within about 0,5 AU, The periods of observation and their relationship to the solar cycle as measured by the monthly running mean values of Sunspot number are shown in Fig. 1. For each conjunction, Table 1 provides date and time of conjunction, the closest approach point of the PVO radio path, the solar pole over which it occurred, and the interval of observation. Only in the case of conjunction IV did PVO actually disappear behind the disk of the Sun (in the northern hemisphere) as seen from Earth.

As mentioned above, tracking of PVO was substantial. The percentages of time during which PVO was tracked for each of the six conjunctions varied between 42 and 82%, and are plotted in Fig. 2a. A total of over 23,000 hrs or almost 1000 days of Doppler scintillation data were obtained during the ±1 20 day intervals of interest. The distribution of Doppler scintillation data with heliocentric distance, for the three combined conjunctions in 1979-1982 representing solar maximum conditions, and the remaining three in 1984-1987 representing solar minimum conditions, are shown in Fig. 3. Although there is less data during solar minimum, the size of the data set is still considerable, and is nearly uniformly distributed over all heliocentric distances. There was generally very little tracking of PVO within a few days of the conjunctions, when the PVO radio path passed over the solar poles and probed the high latitude regions of the solar wind. For this reason, the measurements used in this study are essentially confined to the ecliptic plane.

The Doppler scintillation measurements of this paper are part of the navigation data collected by the NASA Deep Space Network, and used in previous studies (cf Woo, 1988), The rms Doppler scintillation is computed every 3 reins for Doppler data sampled at a rate of one per 10 s. Two modes of radio transmission are used for tracking spacecraft. In the one-way mode, the spacecraft signal is transmitted to the ground receiver, while in the two-way mode, it is transmitted from Earth to spacecraft and back to Earth. Except for some one-way measurements near the Sun, most of the scintillation data were obtained in the two-way radio transmission mode. Artifacts in the Doppler data due to errors in measurements or predictions of the spacecraft trajectory were removed, and transients identified by visual inspection of Doppler scintillation time series plots. The procedure and caveats in identifying the transients have been described and discussed in Woo (1988). In order to ensure uniformity of the selection criteria over the entire current data set, and in light of some insight gained from recent comparisons of Doppler scintillation and *in situ* plasma measurements (Woo and Schwenn, 1991), the 1979-1982 PVO data were reexamined, and as a result, eight more transients were added to the 98 PVO transients compiled in Woo (1988).

TRANSIENT RESULTS

A total of 142 transients were identified during the 1979-1987 period of study. The number of transients identified for each superior conjunction are shown in Fig. 2b, and vary from a high of 43 in 1981 to a low of 8 in 1986, a drop by more than a factor of five. The process of identifying transients is subjective and at times uncertain for low level and/or slow-rise-time events, in particular. However, the number of questionable transients was generally small, amounting to only a few percent of the total number during solar maximum. As a result of the significantly lower number of transients during solar minimum, uncertainties were higher during solar minimum but still less than 20%.

Transient rates corresponding to the results in Fig, 2b are shown in Fig. 2c, which indicate a high of 0,22 in 1979 and a low of 0.077 transients/day in 1986. The results during the period 1979-1982 are consistent with those obtained before based on a larger data set (Woo, 1988). As shown in Fig. 2b, tracking and therefore data coverage was lower in 1986 than in other years. Because of data gaps, there is greater uncertainty associated with the transient rate of 1986. Nevertheless, the trend of the Doppler scintillation transient rate is clear and distinct, showing a decrease by almost a factor of three from 1979 to 1986.

The transient rate results are plotted with Sunspot number in Fig. 3, where the vertical scales for transient rate and Sunspot number have been adjusted to facilitate comparison of the two results. The significant drop in transient rate during solar minimum conditions tracks the Sunspot number both in magnitude and phase remarkably well, and represents a particularly strong variation when compared with that of other aspects of Doppler scintillation, e.g., radial dependence and mean level (Woo and Armstrong, 1992). It is interesting that the observed difference in transient rate between solar minimum and solar maximum conditions stems mainly from transients within 60 R_o, as illustrated in Fig. 4 showing the distributions of transient rate with heliocentric distance for conjunctions 1-111 (solar maximum) and conjunctions IV-VI (solar minimum). in 1981-1982, comparisons with radially aligned *in situ* plasma measurements found that most of the scintillation transients represented interplanetary shocks and their trailing turbulent plasma. It is interesting that, like Doppler scintillation transients, the number of shocks directly observed in the solar wind is considerably reduced during solar minimum conditions (Volkmer and Neubauer, 1985).

Other differences have been found between the solar minimum and solar maximum transients. The enhancement in scintillation level, the ratio of the peak to pre-transient scintillation level (EF for enhancement factor), characterizes the magnitude of the transient. Shown in Fig. 5 are values of EF for conjunctions 1-111 and IV-VI. As in previous studies covering solar maximum conditions, EF tends to diminish with increasing heliocentric distance (Woo, 1988). Since EF serves is an indicator of propagation speed, the decrease in EF is a manifestation of deceleration with heliocentric distance of fast moving transients, most of which are major interplanetary shocks (Woo et al., 1985). By contrast, the Doppler scintillation transients during solar minimum conditions tend to have values of EF that are more evenly distributed with heliocentric distance and that are low (EF < 23), indicating slower moving disturbances. These results indicate that the occasional large transients representing fast-moving interplanetary shocks are present during solar maximum are very rare during solar minimum. A total of 13.2% of the solar maximum transients had values of EF exceeding 32, the highest value of EF during solar minimum. As reported previously (Woo, 1988), there is often much uncertainty in determining the duration of transients and we have not attempted a formal statistical study. However, in general, the transients during solar minimum appear a bit longer than those during solar maximum, perhaps a consequence of slower moving disturbances during solar minimum.

Although more detailed comparisons of individual cases of coronal mass ejections and Doppler scintillation transients are underway, most Doppler scintillation transients are the interplanetary manifestation of coronal mass ejections observed in white-light coronagraphs (Woo et al., 1982;1985). It is therefore interesting to compare whole-Sun CME and Doppler transient rates. Shown in Fig. 6 are the annual CME rates during the interval of 1979-1987 obtained by Webb (1992) from the Solwind and SMM coronagaphs after corrections for duty cycle and longitudinal visibility function of each observing instrument were made, Although there are discrepancies between the Solwind and SMM rates, presumably due to differences in field of view of instrument, sensitivity of instrument, duty cycle, tracking coverage and procedure for selecting CMEs, the trend is clear. The Doppler scintillation transient rate results plotted in Fig. 6, where the vertical scales for transient and CME rates have been adjusted to facilitate comparison, show very good correlation with the CME rate.

Further comparisons can be made by converting Doppler scintillation transient rates to equivalent but approximate full-Sun CME rates. First, we multiply the Doppler transient rate by a factor of two to account for the fact that the radio path is only probing the solar wind off one of the two limbs (east or west) of the Sun. Second, although Doppler scintillation is an integrated line-of-sight measurement, because of the approximate inverse-square radial dependence of the electron density fluctuation, most of its contribution comes from that portion of the radio path covering a longitudinal range of about 50° (Woo, 1975). Assuming that the CMES are uniformly distributed over all longitudes, we multiply the Doppler scintillation rate by an additional factor of three (rather than 180/50= 3.6 to make allowance for the longitudinal extent of the CME) to convert to a rate covering a longitudinal range of 180°, Finally, the Doppler scintillation measurements take place essentially in the ecliptic plane. Histograms of coronal mass ejections observed under solar maximum conditions show that they are concentrated primarily at low solar latitudes near the equator, that they have a typical angular width of 40-45°, and that observations confined to the ecliptic plane would detect about half of the CMEs over the full range of latitudes (Howard et al., 1986, Hundhausen, 1993). The rate of Doppler scintillation transients under solar maximum conditions can, therefore, roughly be converted to the full-Sun CME rate by multiplying the scintillation transient rate by the factor (2)(3)(2)=12. The Doppler transient rate in 1981 was 0.21 transients/day, so that multiplying this by 12 gives a full-Sun rate of 2.5 CMEs/day, close to the observed CME rate displayed in Fig. 6.

During solar minimum, histograms of CMEs show that there are very few CMEs at the high latitudes, and that the angular span of the CMEs is narrower than that during solar maximum (Howard et al., 1986, Hundhausen, 1993). Since the Doppler scintillation measurements that are confined to the ecliptic plane would essentially capture all of the CMEs, the Doppler scintillation transient rate must be multiplied by the factor (2)(3)=6 to convert to full Sun CME rates. The transient rate of ().077 transients/day in 1986 would thus convert to 0,46 CM Es/day, again close to the observed CME rate near solar minimum.

The above calculations depend on approximations and assumptions about two different types of observations and properties of the CMES themselves. They are not expected to provide precise agreement, but they do show that coronal mass ejections and Doppler scintillation transients are closely related to each other, not just during solar maximum as occasional individual comparisons have shown in the past (Woo et al., 1982, 1985; Bird et al., 1985), but throughout the entire solar cycle. Since Doppler scintillation transients usually represent enhancements in electron density fluctuation, which is generally proportional to the mean, by their very nature, Doppler scintillation transients would be expected to be closely related to the CMEs detected by both coronagraphs and zodiacal light photometers (Jackson, 1985; Webb, 1991). Another interplanetary signature that appears to be highly correlated with CMEs is the counterstreaming solar wind electron event (Gosling et al., 1992),

CONCLUSIONS

Systematic analysis of the unique and extensive PVO Doppler data set inside 0.5 AU during 1979-1987 has made it possible to extend previous statistical results of Doppler scintillation transients to include solar cycle minimum conditions. A total of 142 transients, of which 36 occurred during the low solar activity period of 1984-1987, have been identified. Transient rates vary from a high of 0.22 in 1979 (one transient every 4.6 days) to a low of ().077 transients/day in 1986 (one transient every 13 days), a decrease by almost a factor of three from solar maximum to solar minimum. This solar cycle variation, the strongest yet of any solar wind Doppler scintillation property, is highly correlated with both Sunspot number and the frequency of occurrence of CMEs observed by coronagraphs. The correlation of Doppler scintillation transients with CMEs during solar maximum conditions of 1979-1983 is not surprising, since CMEs, Doppler scintillation transients and interplanetary shocks are closely associated during this time (Woo et al., 1985; Sheeley et al., 1985, Woo and Schwenn, 1991).

Aside from frequency of occurrence, the Doppler scintillation transients during the low solar activity period of 1984-1987, particularly those closer than 60 R_o, appear different from those during solar maximum, The magnitudes of the transients as characterized by the enhancement in scintillation level are lower, the durations somewhat longer, and the time profiles less dramatic. These transients will form the basis for detailed comparisons with CMEs observed by both Solwind and Solar Maximum Mission coronagraphs, and direct fields and particles measurements made at the orbits of Venus and Earth by the PVO and IMP spacecraft, respectively. These investigations promise to reveal much about interplanetary disturbances and large-scale solar wind structure near the Sun, their relationship to CMEs, their evolution with heliocentric distance, and their relationship to recurrent high-speed streams.

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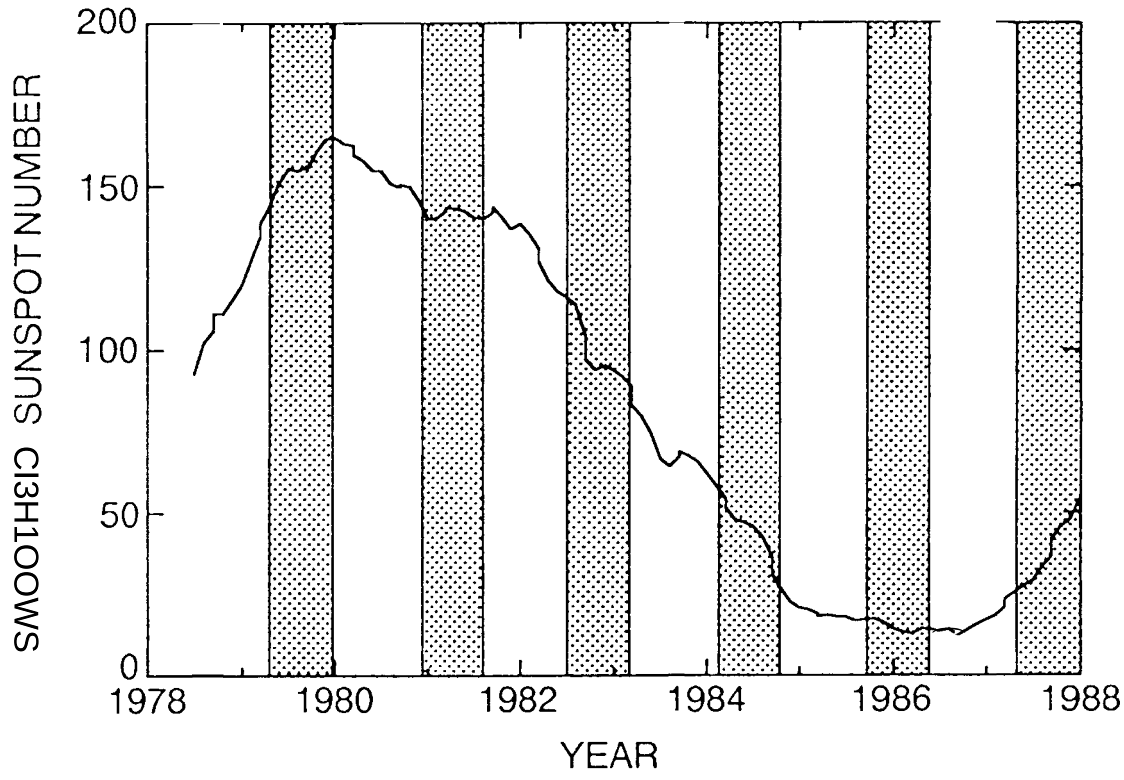
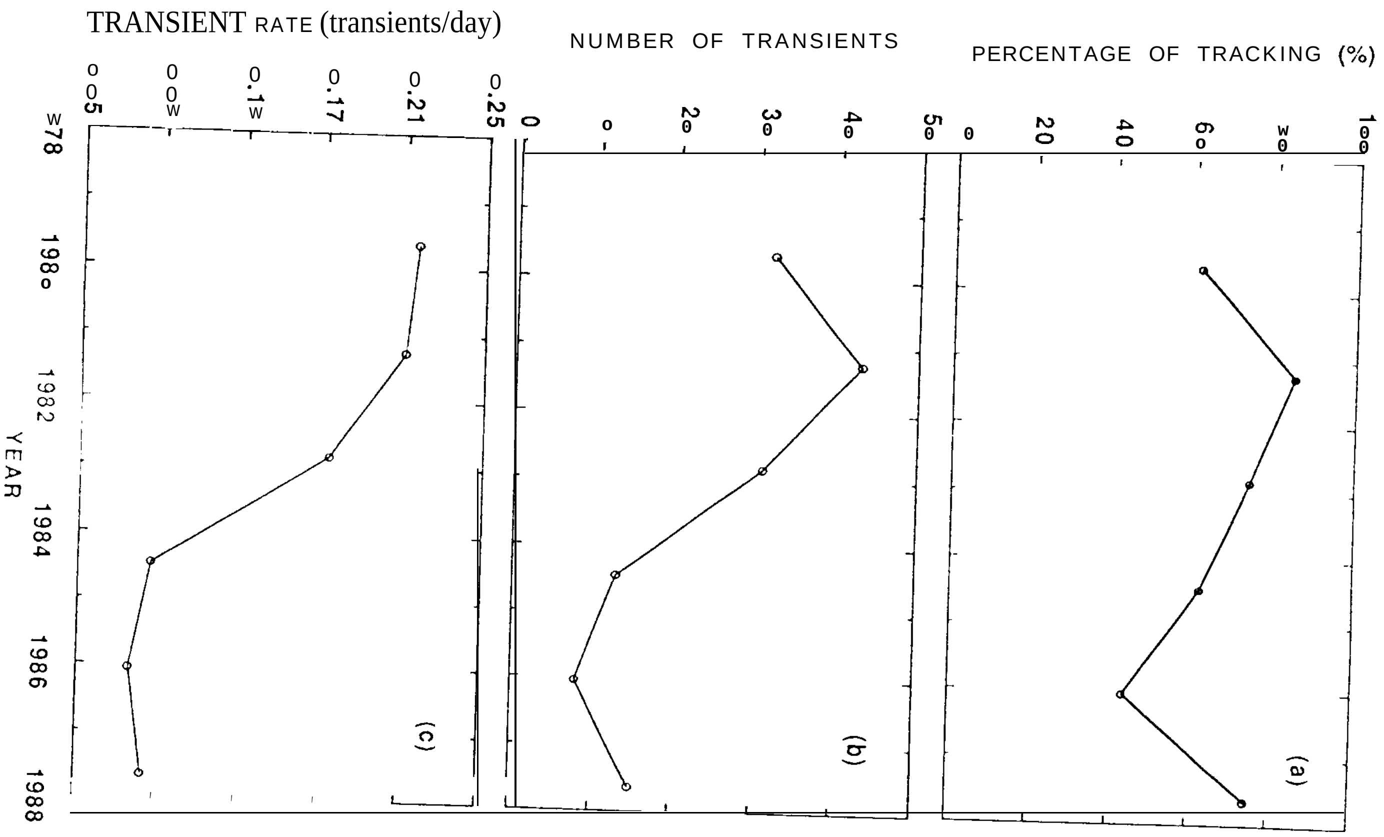
LIST OF FIGURES

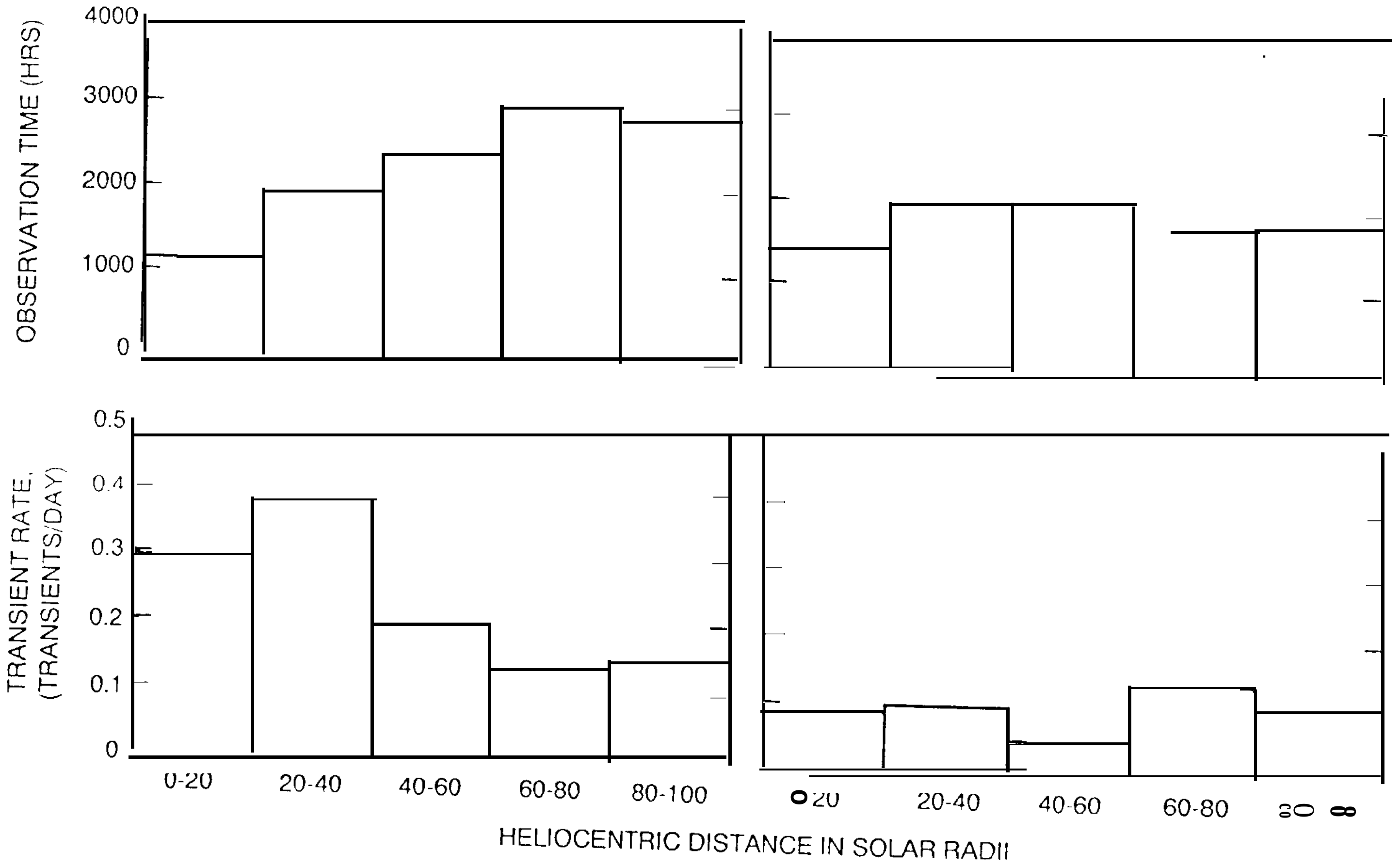
TABLE 1. Summary of Pioneer Venus Superior Conjunctions

Superior Conjunction	Date of Conjunction	Time in UT	Distance in R_O	Solar Pole	interval of Transient Study
I	August 25, 1979	1200	5.1	N	April 27, 1979- December 23, 1979
11	April 7, 1981	0900	4.6	S	December 6, 1980 - August 5, 1981
III	November 4, 1982	0200	3.1	N	July 6, 1982- March 4, 1983
IV	June 15, 1984	2300	0.8	N	February 16, 1984 - October 13, 1984
v	January 19, 1986	1600	3.7	s	September 21, 1985- May 19, 1986
VI	August 23, 1987	0600	5.1	N	April 24, 1987- December 21, 1987

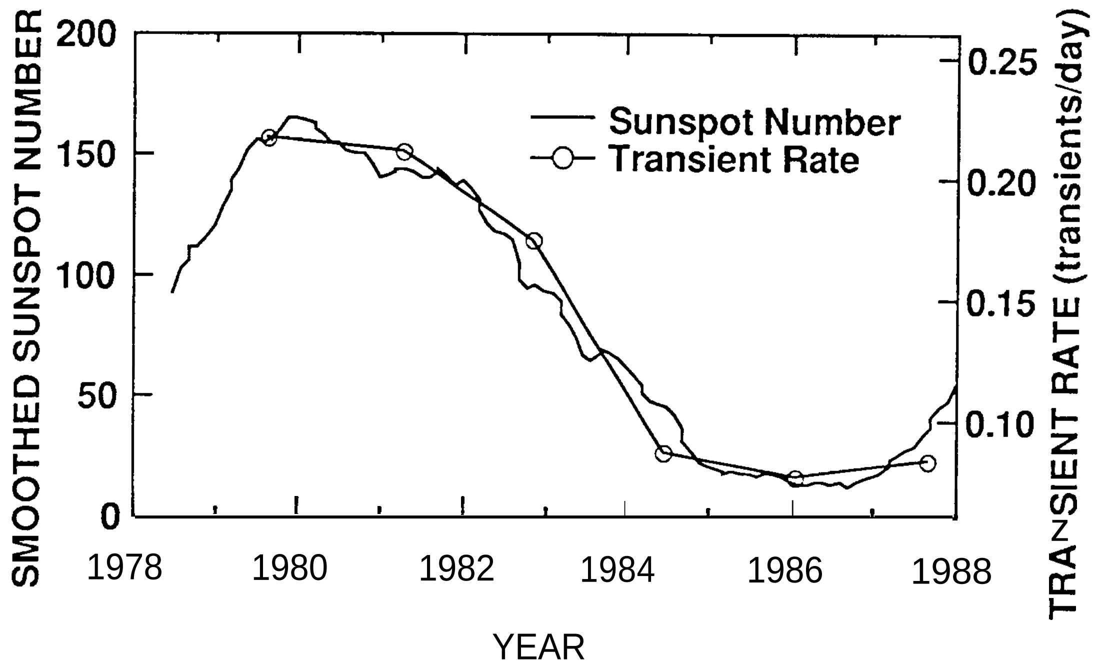

200
150
100
50
0
1978
1980
1982
1984
1986
1988
YEAR
SMOOTHEIC SUNSPOT NUMBER



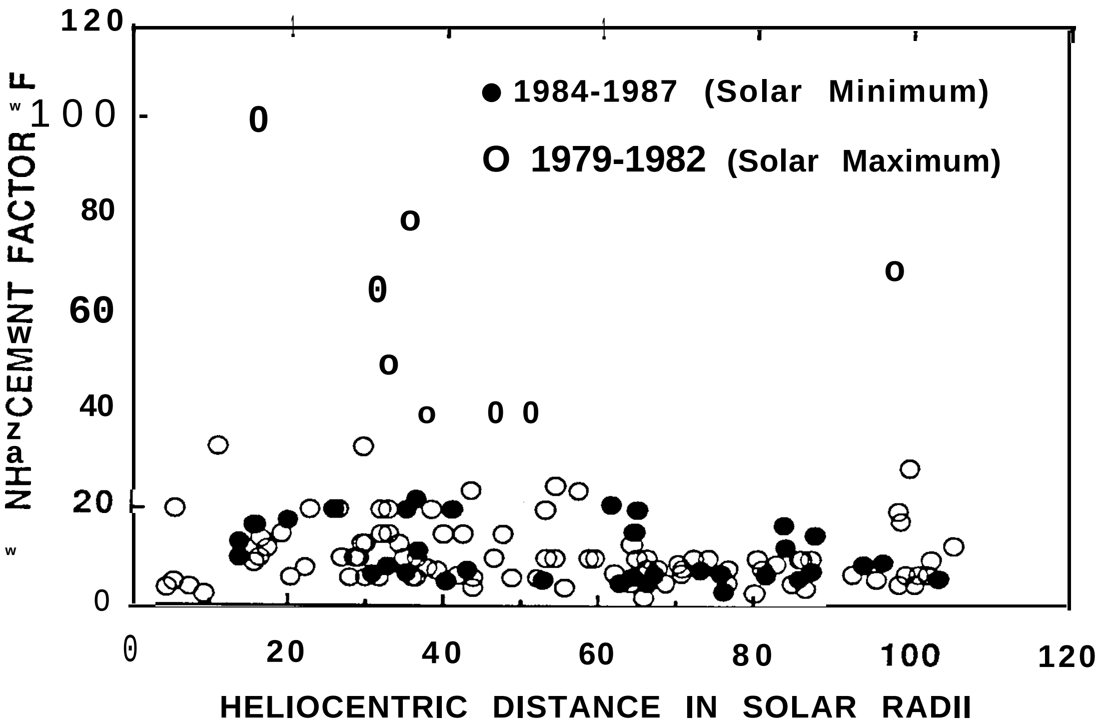
TRANSIENT RATE (transients/day)
NUMBER OF TRANSIENTS
PERCENTAGE OF TRACKING (%)
YEAR
1982
1984
1986
1988
(a)
(b)
(c)



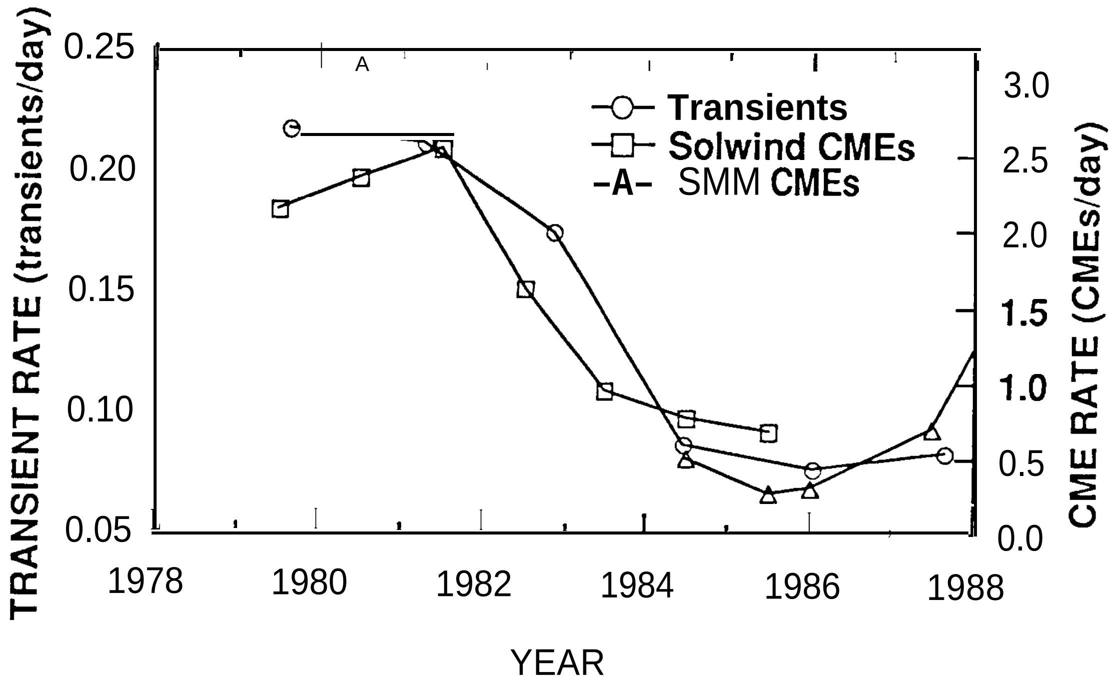
OBSERVATION TIME (HRS)
4000
3000
2000
1000
0
TRANSIENT RATE.
(TRANSIENTS/DAY)
0.5
0.4
0.3
0.2
0.1
0
0-20
20-40
40-60
60-80
80-100
20-40
40-60
60-80
HELIOCENTRIC DISTANCE IN SOLAR RADII



SMOOTHED SUNSPOT NUMBER
200
150
100
50
0
1978
1980
1982
1984
1986
1988
YEAR
Sunspot Number
Transient Rate
0.25
0.20
0.15
0.10
TRANSIENT RATE (transients/day)



ENHANCEMENT FACTOR
120
100
80
60
40
20
0
● 1984-1987 (Solar Minimum)
O 1979-1982 (Solar Maximum)
0
20
40
60
80
100
120
HELIOCENTRIC DISTANCE IN SOLAR RADII


TRANSIENT RATE (transients/day)
0.25
0.20
0.15
0.10
0.05
Transients
Solwind CMEs
SMM CMEs
3.0
2.5
2.0
1.5
1.0
0.5
0.0
CME RATE (CMEs/day)
1978
1980
1982
1984
1986
1988
YEAR